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W. W. HANSEN LABORATORIES OF PHYSICS

STANFORD UNIVERSITY . STANFORD, CALIFORNIA

MICROWAVE RESEARCH

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Microwave Laboratory
W. W. Hansen Laboratories of Physics
Stanford University
Stanford, California

INTRODUCTION

This report is the Seventeenth Quarterly Status Report under Contract Nonr 225(48), which began on 1 February 1959, and it reports the period of 1 February through 30 April 1963. At the present time there are four projects active under this contract:

I. Acoustic wave amplification studies
II. Optical masers
III. Ferrite nonlinear propagation
IV. Plasma harmonic generation

During this quarter three projects were completed; a technical report was written and distributed for each one. They are:

1. The project formerly titled "Transverse-wave Frequency Doublers" has been reported in "The Theory and Application of Some Transverse-wave Interactions," by R. E. Hayes, M. L. Report No. 1025.

2. The project formerly titled "Parametric Refrigeration" has been reported in "Nonlinear Effects in Longitudinal Electron-Stream Slow-Waveguide Systems," by G. C. Van Hoven, M. L. Report No. 1026.

3. The project formerly titled "Nonlinear Quantum Effects" has been reported in "Nonlinear Quantum Effects" by R. G. Smith, M. L. Report No. 1027.

Certain introductory parts of these projects will be repeated each time so that the reader may more readily follow the work without reference to previous reports.

The Responsible Investigator for this contract is M. Chodorow.

I. ACOUSTIC WAVE AMPLIFICATION STUDIES

(C. F. Quate,* K. Blotekjaer, A. Tonning, W. H. Haydl, C. D. W. Wilkinson)

A. OBJECTIVE

This project is devoted to the studies of the microwave region of acoustic wave amplification in piezoelectric semiconductors. The first experiments on this project were reported by Hutson, McFee and White[1] wherein they demonstrated that electrons drifting through Cadmium Sulphide could give up energy to the acoustic waves if the electrons were drifting faster than the velocity of sound. Both the drifting carriers and the elastic media can support propagating waves which are coupled by the electric fields in the piezoelectric crystals. When the carriers drift with an average velocity slightly lower then the velocity of sound, they absorb energy from the acoustic waves, and when their drift velocity exceeds the velocity of sound, they give up energy to the elastic waves. It is an important principle which demonstrates strong cumulative interaction between traveling waves and the conduction electrons. The simple theory of the process would indicate that the amplification process should be valid well into the microwave range. It is our objective to investigate the nature of the amplifying process at these higher frequencies.

B. PRESENT STATUS

1. Experimental Results

We have continued the study of the acoustic gain for a CdS wafer 1.08 mm in length. The gain vs applied voltage at 550 Mc is shown in Fig. 1 together with the calculated curve, assuming a mobility of 200. The measured values are within a factor of two of the theoretical values. We believe that the minimum is too shallow because of nonuniform illumination over the cross-section of the

*Project supervisor.

[1] A. R. Hutson, J. H. McFee, D. L. White, "Ultrasonic Amplification in CdS," Phys. Rev. Letters 7, 237 (September 1961).

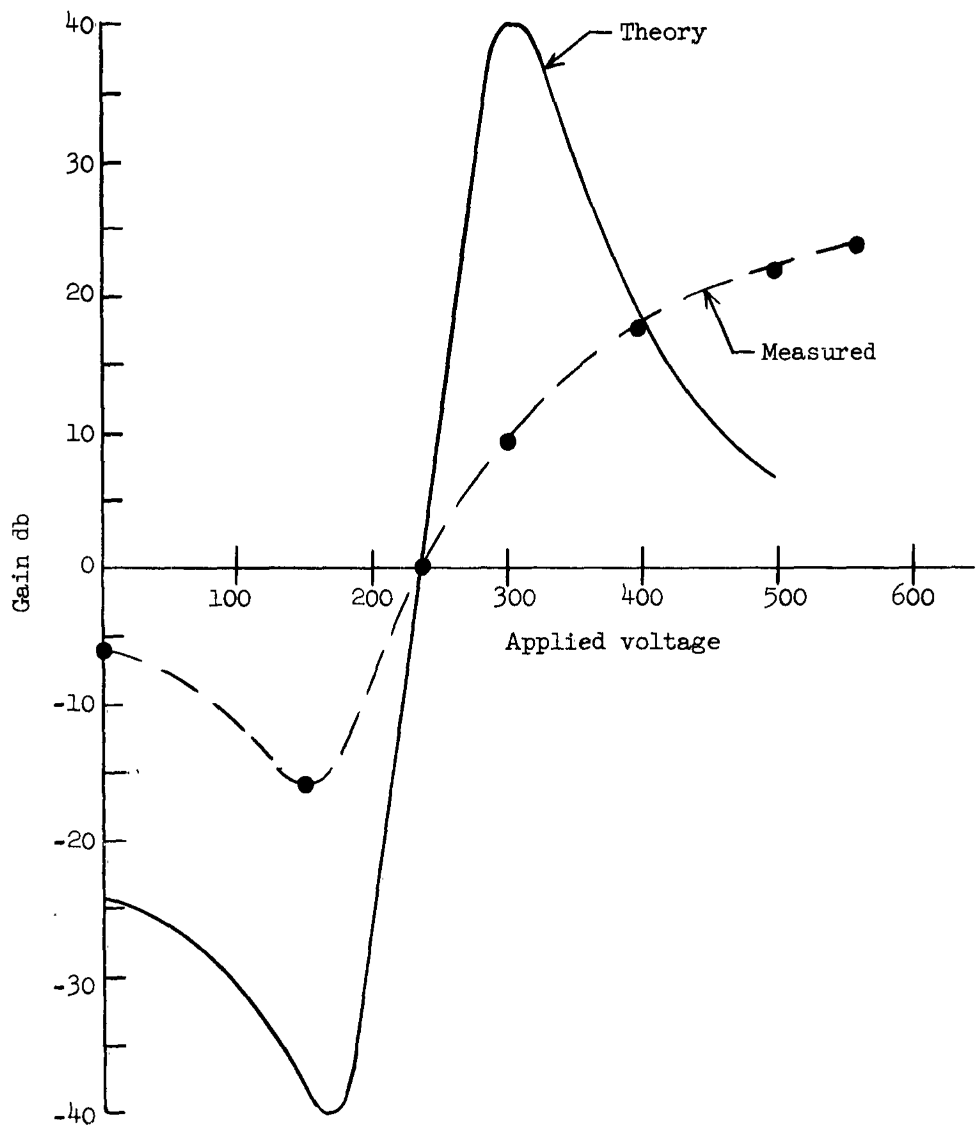

Theory
Measured
Gain db
Applied voltage
40
30
20
10
0
-10
-20
-30
-40
100
200
300
400
500
600

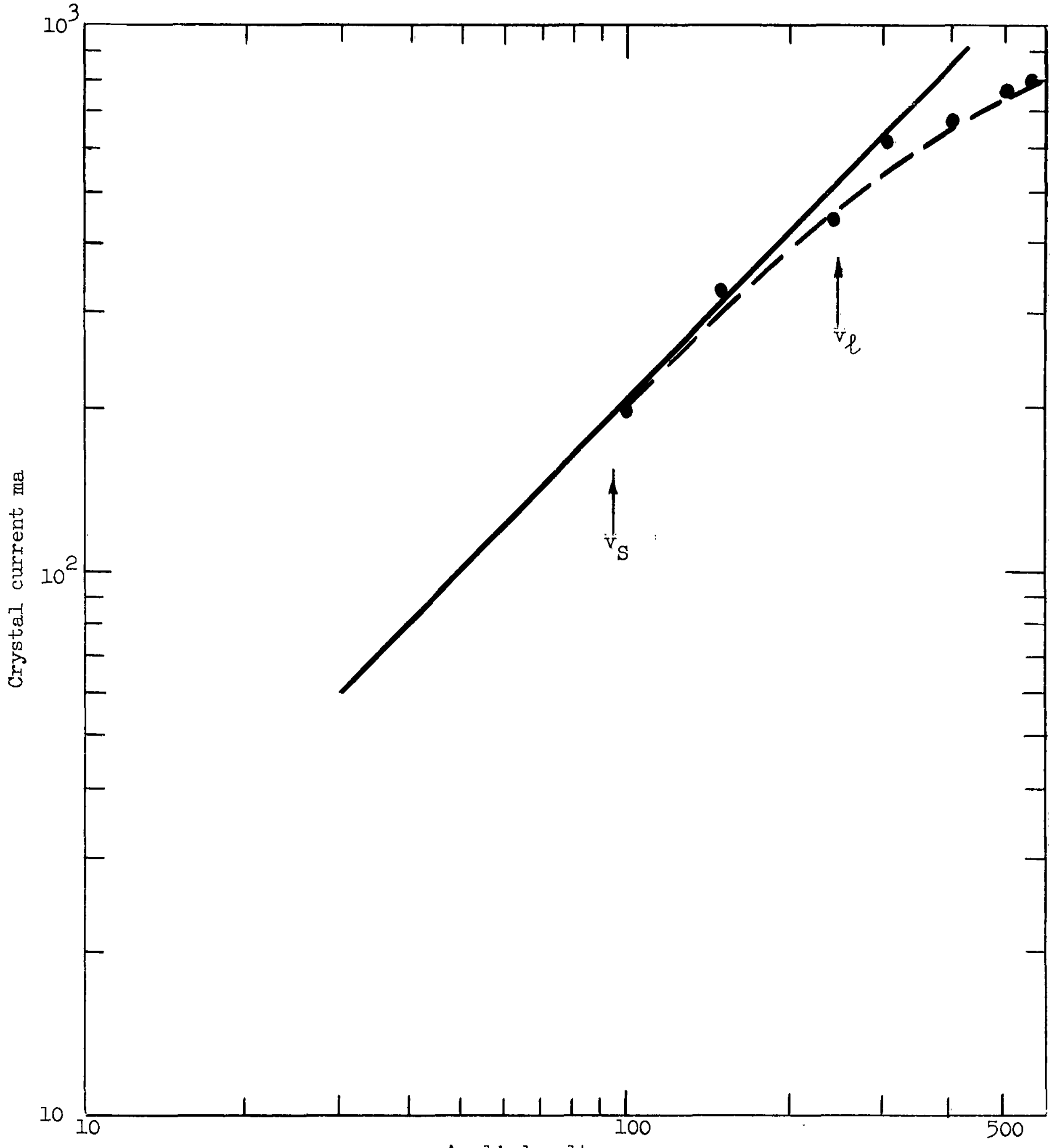
FIGURE 1

sample. With improved illumination we have observed a minimum in excess of 25 db. The maximum gain is less than the theoretical for quite a different reason. As the field is increased the crystal begins to oscillate internally and limit the drift velocity. This is exhibited in two ways. First, we observe a break in the I-V characteristic as shown in Fig. 2. Second, we observe an oscillation spectrum in the crystal current. This was reported in the last report, and a typical output is shown in Fig. 3. We believe these to be shear modes, for they do not appear in the output acoustic waves except under a few critical conditions.

We have worked on the problem of contacts, for in our work we have assumed that the contacts are ohmic and that the field is uniform throughout the crystal. This in fact is not true, for the field variation may vary in one of three ways as shown in Fig. 4. First, with ohmic contacts on an insulating crystal we can have the space-charge limited law. This is not important in our work and we have not observed it. The second case is that of linear variation of voltage (and uniform field). This occurs in conducting crystals with ohmic contacts and is the condition we believe to have achieved in taking the data of Fig. 1. The third case, as illustrated, occurs with nonohmic contacts. When the field is applied, a dipole layer is formed at the barrier layer, which results in a nonuniform field within the crystal.

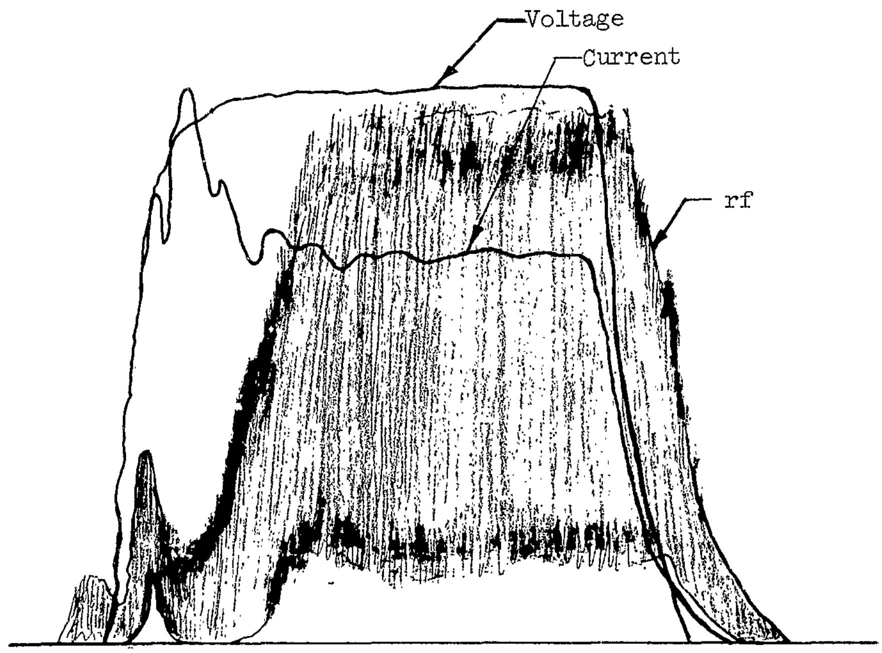
When the field is turned on, the electron current can flow freely until the dipole layer has been formed and the field within the crystal is linear as in Fig. 4b. However, under steady-state conditions with a barrier formed at the contact the potential distribution in the crystal is as shown in Fig. 4c.* It is not uniform and acoustic gain occurs only over a short region of the crystal. Thus we postulate that the peak gain of Fig. 5 occurs while the field is uniform through the crystal. The lower level of gain through the plateau occurs when the field distribution becomes nonuniform due to the barrier. To check this we modified the contacts so that they were ohmic and found the results as in Fig. 6. We report on this in order to stress the obvious result that one should exercise great care to insure ohmic contacts to the crystal.

*This is the same phenomenon that N. F. Foster and D. L. White exploit for "diffusion layer transducers." See J. Appl. Phys. 34, 990 (1963).



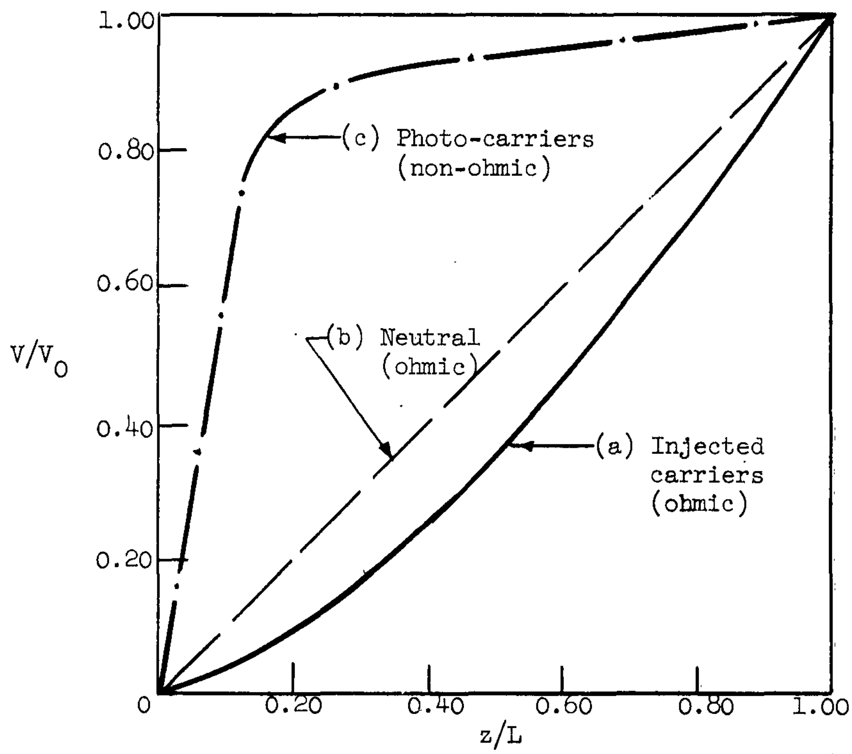
10^3
10^2
10
Crystal current ma
10
100
500
Applied voltage
v_S
v_ℓ

FIGURE 2



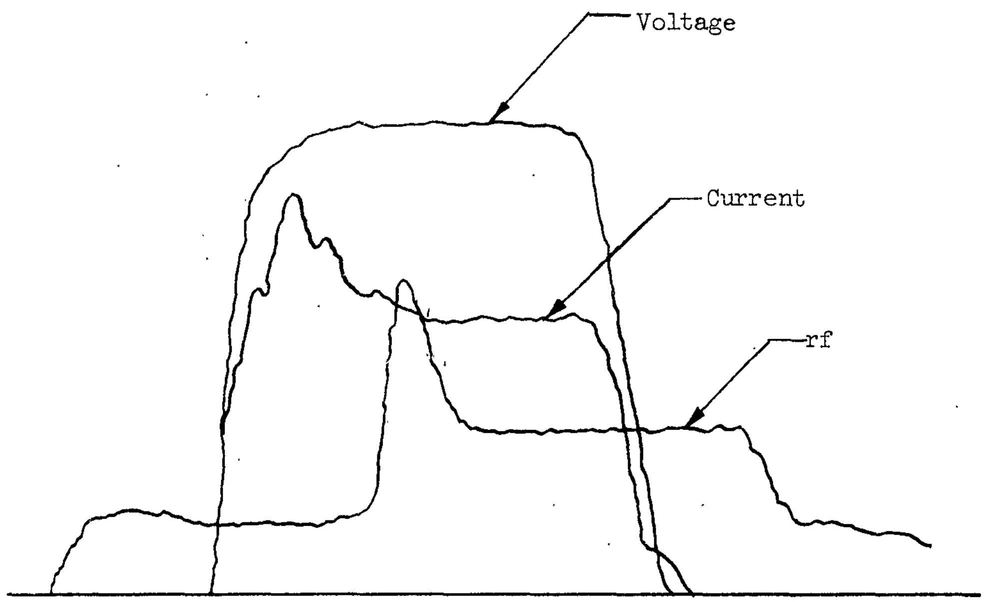
Noise current in crystal leads at 360 Mc.
(Horizontal scale = 2 μs/cm)
(Vertical scale = 100 v/cm and 100 ma/cm).

FIGURE 3



Field distribution within a crystal

FIGURE 4



Variation of gain at 675 Mc.
Peak gain = 20 db   Plateau gain ~ 14 db
(Horizontal scale = 2 μs/cm)
(Vertical scale = 100 v/cm and 100 ma/cm).

FIGURE 5

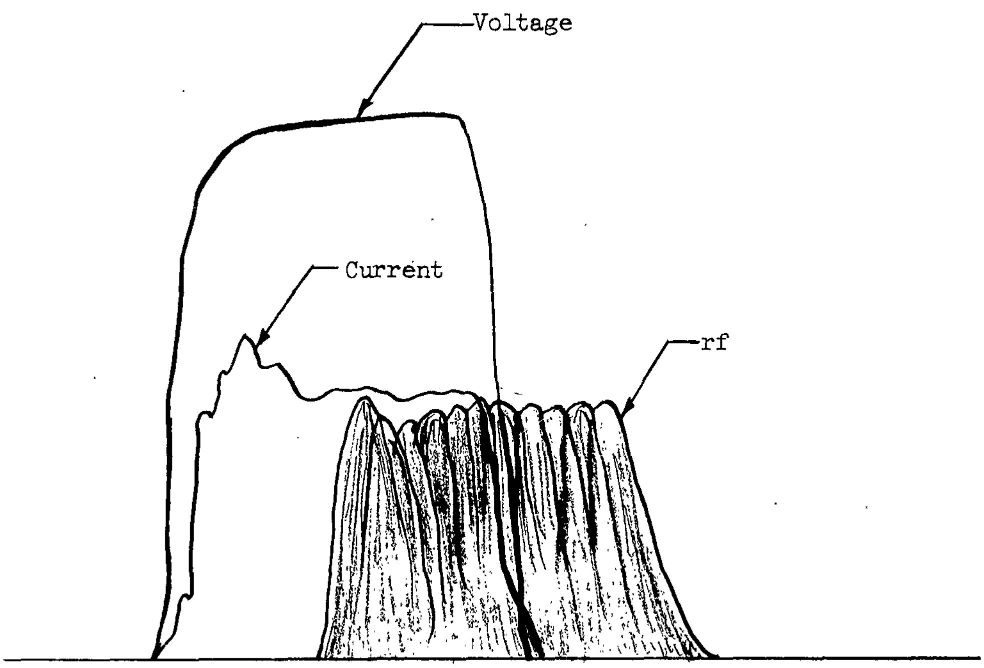


Illustration of gain versus time for a neutral crystal. Peak gain = 20 db f = 550 Mc
(Horizontal scale = 2 μs/cm)
(Vertical scale = 100 v/cm and 250 ma/cm).

FIGURE 6

We are now fairly well satisfied with the gain mechanism and we plan to turn our attention to the two problems of transducers and oscillation suppression before proceeding to higher frequencies.

2. The Effect of Nonzero Hole Mobility

We have considered theoretically the possibility of avoiding oscillations by using a material with electron and hole mobilities of the same order of magnitude. If the parameters are chosen such that the hole drift velocity is appropriate for maximum attenuation, the damping of the backward acoustic wave may be sufficient to suppress oscillations.

We have considered this problem in detail, using electronic computers, and the results show that there exist reasonable ranges of parameter values for which stable operation is possible. The effect of nonzero hole mobility is demonstrated in Fig. 7, where the gain of the forward wave and the attenuation of the backward wave are plotted vs electron drift velocity. The amplifier may oscillate in regions where the forward gain exceeds the backward attenuation. Increasing the hole mobility from zero to 0.3 of the electron mobility leaves the forward gain practically unchanged, whereas the backward attenuation increases sufficiently to make the amplifier unconditionally stable for the important values of drift velocity.

3. Coupling via Deformation Potential

We are considering the possibility of making use of phonon-electron interaction by means of the deformation potential and have done some preparatory theoretical work in this direction. It turns out that this form of interaction may be expressed mathematically by a set of linear equations that are closely analogous to the piezoelectric equations.

By a simple thermodynamic argument, regarding the crystal as a continuum, it is possible to show that

$$\zeta - \zeta_0 = a(N - N_0) + C_{ik}\, u_{ik}$$

$$\sigma_{ik} - \sigma_{ik}^0 = C_{ik}(N - N_0) + \lambda_{ikmn}\, u_{mn} \quad ,$$

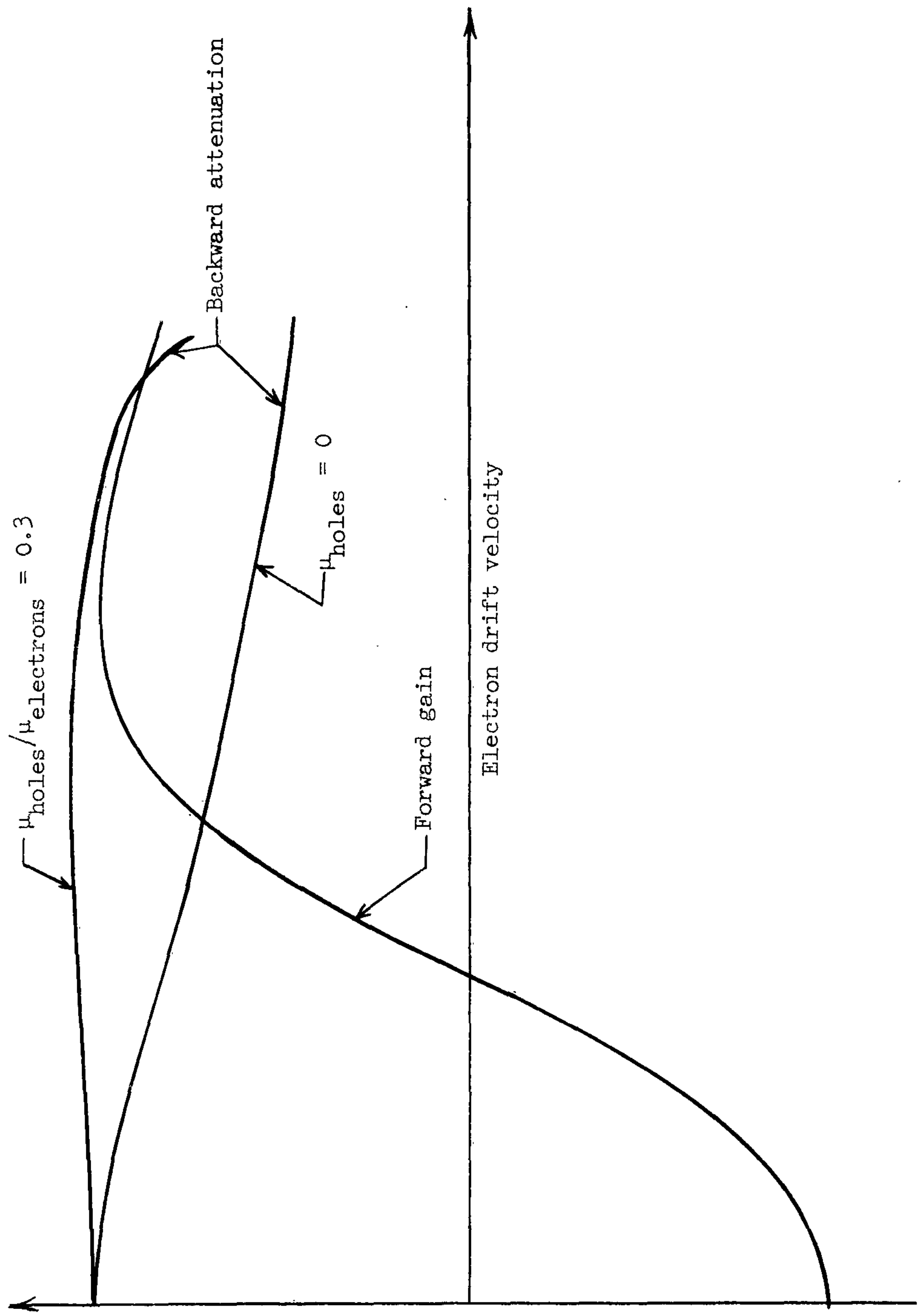

Backward attenuation
$\mu_{holes}/\mu_{electrons} = 0.3$
$\mu_{holes} = 0$
Forward gain
Electron drift velocity

FIGURE 7

where the summation convention is used and

λ_{ikmn} is the elastic tensor of the crystal,
u_{nm} is the strain tensor,
σ_{ik} is the stress tensor,
ζ is the chemical potential of the conduction electrons,
N is the electron density,
ζ_0 , σ^0_{ik} and N_0 are equilibrium values of the respective quantities
$1/a \approx g(\zeta)$ is the density of electron states at the Fermi level.

The first equation shows that the energy of an electron depends on the strain through the term $C_{ik} u_{ik}$. Hence C_{ik} is the deformation potential tensor introduced by Bardeen and Shockley.

The second equation shows that the stress of the crystal depends on the electron density through the same tensor C_{ik} . This equation makes explicit the action of the electrons in the solid in which they are contained. The term $C_{ik}(N - N_0)$ may be interpreted as the stress contributed by the pressure of the electron gas.

II. OPTICAL MASERS

(A. L. Schawlow,* H. W. Moos, G. F. Imbusch, L. Mollenauer)

A. OBJECTIVE

The purpose of this work is to improve and extend the performance of optical masers, so that they can be used for physical research problems. It is desired to make optical masers approach more nearly the ideal characteristics of extreme monochromaticity, high power and directionality. It is also desired to have optical masers operating at a wide range of wavelengths. Wherever the characteristics of available optical masers are adequate, it is intended to apply them to appropriate problems in physics, and to the realization of new kinds of instruments.

B. PRESENT STATUS

1. <u>Monochromatic Ruby Optical Maser</u>

A report on the previous experimental and theoretical work was completed and presented at the Polytechnic Institute of Brooklyn Symposium on Optical

*Project supervisor.

Masers, April 16-18, 1963. The report is "The High Gain Laser as a Wavelength Standard," by L. F. Mollenauer, G. F. Imbush, H. W. Moos, and A. L. Schawlow. This will be published in the Proceedings of the Symposium in the fall of 1963.

2. Multiple Beam Interferometry with Large Plate Separation

The work described in the previous report was reported at the Optical Society of America Meeting, March 25-27, 1963.

III. FERRITE NONLINEAR PROPAGATION

(B. Auld,* D. K. Winslow, M. Omori)

A. OBJECTIVE

The objective of this project is to investigate nonlinear microwave propagation in gyromagnetic media. Up to the present time the principal emphasis has been on the study of frequency doubling in propagating circuits. Other topics to be investigated include mixing, shock-wave formation, parametric amplification, electromagnetic instabilities analogous to Suhl spin wave instabilities, and jump phenomena in propagating systems.

B. PRESENT STATUS

During this quarter three topics in parallel pumping were studied theoretically as well as experimentally. The experiments were performed using a loop to couple between the sample and the transverse field.

Nondegenerate Parallel Pumping

1. Frequency Mixing

(a) h_p Variation.

A frequency mixing effect is predicted when the uniform precession at ω_s is subject to nondegenerate parallel pumping at ω_p. Mixed frequency components of $m\omega_p + n\omega_s$ are generated by a time variable coefficient in the equations of motion, which are linear. Among the mixed components, the $\omega_p - \omega_s$ component is dominant when $\omega_p - \omega_s$ is close to ω_s. This condition is assumed in the following report. From the theory, the $\omega_p - \omega_s$

*Project supervisor.

component is a linear function of the parallel pumping magnetic field, h_p . The experimental result, which shows good agreement with the theory, is plotted in Fig. 8.

(b) H_{dc} Variation.

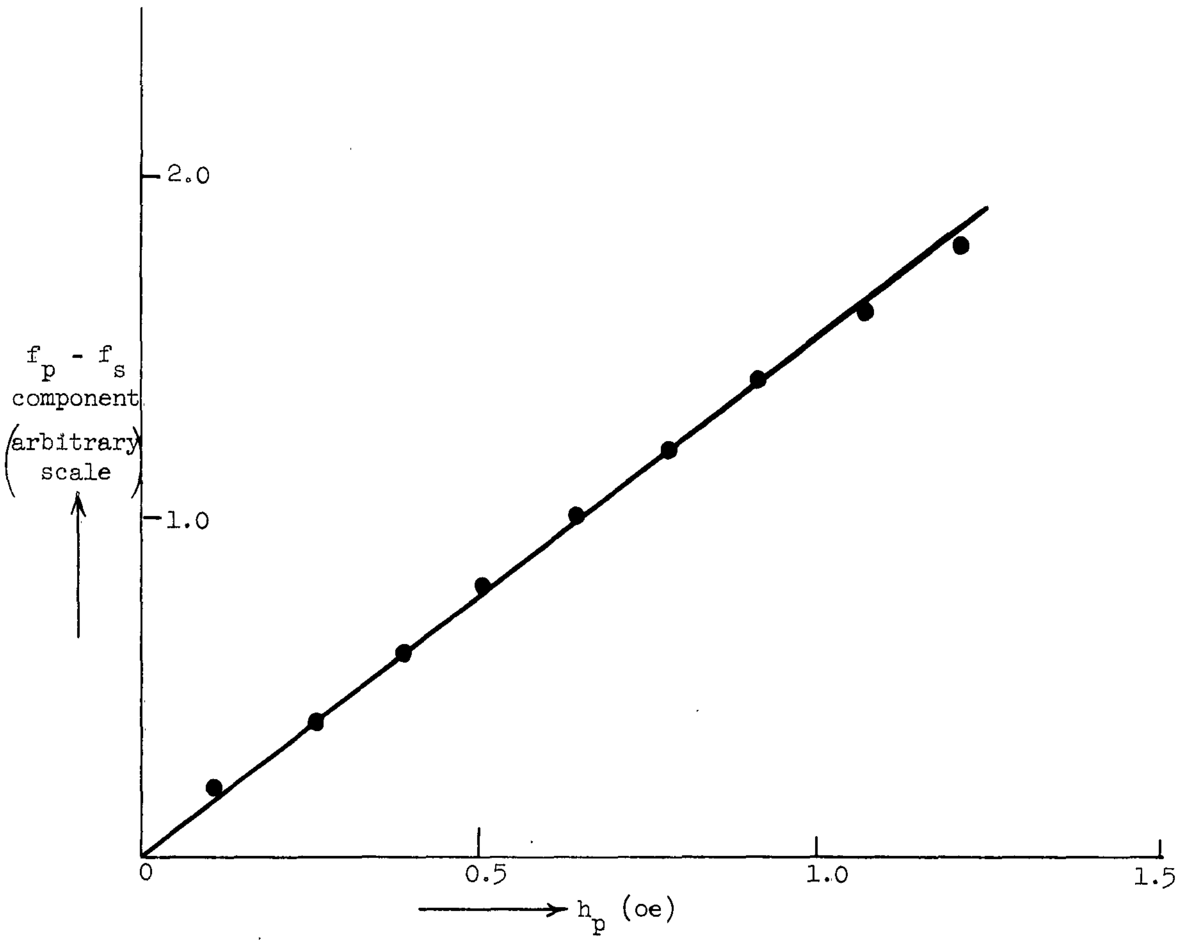
From the theory developed, the $\omega_p - \omega_s$ component has maximum output at two values of H_{dc} , one being the resonance field for ω_s and the other $\omega_p - \omega_s$, and minimum output at the field for resonance at $\omega_p/2$ (see Fig. 9a). In the experiment the $\omega_p - \omega_s$ component is again mixed with the ω_s reflected from the sample by a diode mixer to obtain a video signal with frequency $\omega_p - 2\omega_s$, whose amplitude is proportional to the product of ω_s and the $\omega_p - \omega_s$ component. Since the ω_s reflected has a dip at the field for the uniform precession resonance, the predicted video component has an H_{dc} variation as shown in Fig. 9a. An experimental result for the case of $\omega_p - 2\omega_s = 30$ Mc/s shows good agreement with the prediction (see Fig. 9b).

2. New Method to Measure the Butterfly Curve

In the course of the experiments above, it is found that the parallel pump spin wave instability is easily observed on the transverse driving field side. That is, the reflected transverse driving field from the sample shows an off-resonance effect when the spin wave instability is reached. This is considered to be due to the change of the saturation magnetization caused by the spin wave generation in the sample. The advantage of this method over the conventional method of observing spin wave instabilities is the increase of sensitivity. Figure 10 shows a comparison of the critical field determined from the reflected signal pulse with the critical field determined from the reflected pump pulse. A spike at 2624 oe on the curve measured from the reflected signal pulse is a degenerate parallel pump interaction between the pump, ω_p and the signal, $\omega_s = \omega_p/2$.

3. Parametric Oscillation

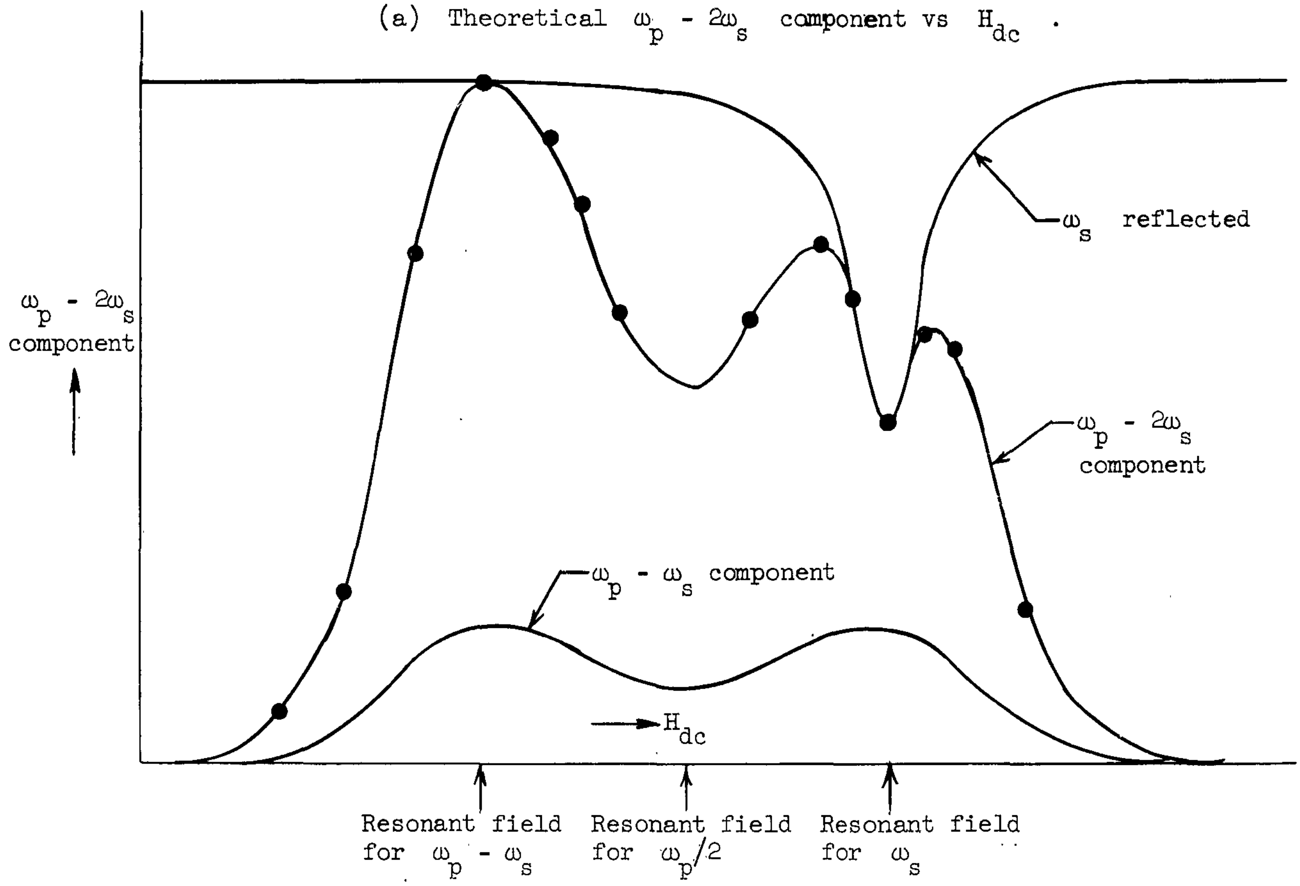
According to the theory the system oscillates parametrically when the parallel pump field exceeds the critical value, $h_{p_{crit}}$. The observed parametric oscillation is shown in Fig. 11.



Amplitude of $f_p - f_s$ component vs pump field.

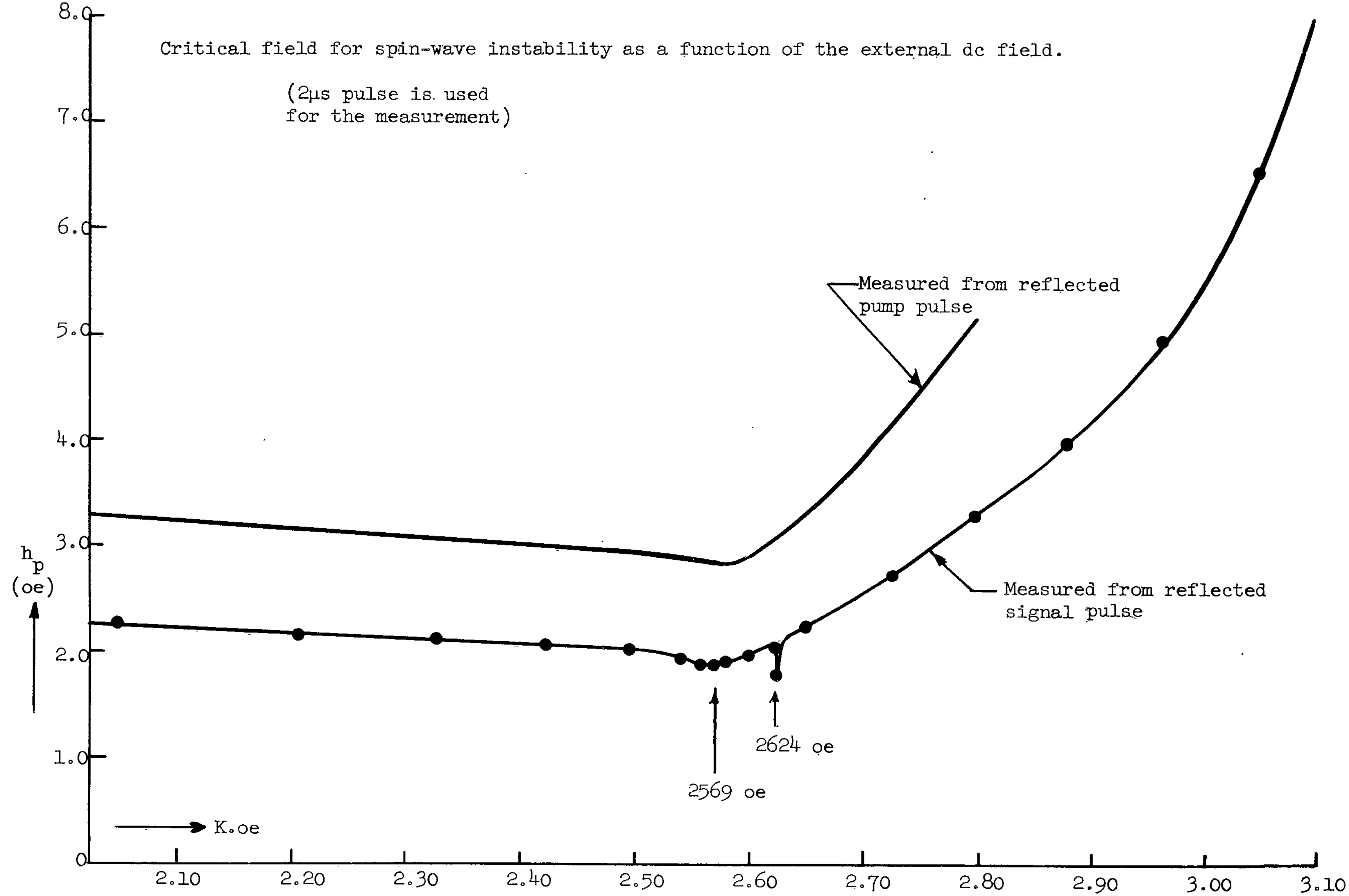
FIGURE 8

(a) Theoretical $\omega_p - 2\omega_s$ component vs H_{dc} .



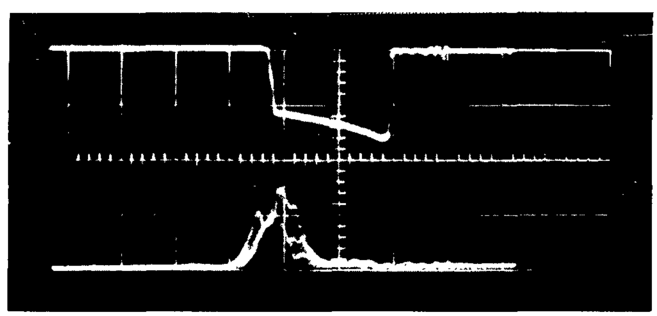
(b) Experimental $\omega_p - 2\omega_s$ component vs H_{ds} .

FIGURE 9



Critical field for spin-wave instability as a function of the external dc field.
(2μs pulse is used for the measurement)
Measured from reflected pump pulse
Measured from reflected signal pulse
2569 oe
2624 oe
h_p (oe)
K.oe
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
2.10
2.20
2.30
2.40
2.50
2.60
2.70
2.80
2.90
3.00
3.10

FIGURE 10



Parametric oscillation by parallel pumping.

FIGURE 11

IV. PLASMA HARMONIC GENERATION

(G. S. Kino,* J. H. Krenz)

A. OBJECTIVE

This project is one in which we hope to generate millimeter-wave harmonics of a high-power fundamental at microwave frequencies by making use of the nonlinear properties of a gas discharge plasma. The objective for this project is twofold: (1) to understand the mechanism controlling harmonic generation in a plasma, and (2) to obtain appreciable rf power at millimeter wavelengths by means of harmonic generation in a nonlinear plasma medium.

B. PRESENT STATUS

During the past quarter a technical report entitled "Harmonic Generation in Plasmas," by J. H. Krenz has been prepared. Significant prior work as well as recent results are included. The abstract is as follows:

"The generation of harmonics due to the nonlinear properties of a microwave plasma discharge was investigated theoretically as well as experimentally. Both high experimental efficiencies along with good theoretical agreements were obtained.

"The nonlinear effects of collisions, spatial variations, and sheaths were also theoretically investigated. In order to obtain the harmonic current due to a velocity-dependent collision frequency, the velocity distribution function was expanded in terms of spatial and time harmonics. By means of successive partial integrations along with the appropriate approximations, the third harmonic current for $\overline{\nu}/\omega$ small was obtained in a particularly convenient form. Collisions, however, were shown to neither account for the observed harmonics nor be an efficient method of harmonic generation.

"The reactive nature of spatial variations is shown to result in particularly strong harmonics. Harmonic currents are shown to result from both a nonuniform rf electric field and a nonuniform plasma density.

*Project supervisor.

A static magnetic field perpendicular to the rf electric field was also included in order to investigate the effect of cyclotron resonance at either the fundamental or second harmonic frequency. While a resonance in second harmonic power is possible if the fundamental rf electric field is held constant, no resonance is obtained if the input power is held fixed. A detailed analysis for the second harmonic generated with a spherically resonant plasma along with good experimental agreement is presented. Harmonics higher than the second are found to depend very strongly upon the plasma sheath region. A simplified sheath model is used to calculate the harmonic currents generated within the sheath. These currents, it is shown, may be rather large and thus account for the higher harmonics.

"The initial experimental results with various modifications of a probe discharge are presented and impedance measurements which result in an increased understanding of the discharge are described. The spatial variation theory is shown to quite readily account for the second harmonic. The techniques developed for confining the discharge at low pressures resulted in higher harmonic efficiencies which seem to indicate that the simple probe discharge may be improved considerably.

"The experimental results of a spherical plasma of the type devised by Swan are also reported. Efficiencies as high as 25% for the second harmonic were readily obtained. The high efficiency was found to be the result of spatial variations within the body of the plasma and a resonance at the harmonic frequency. Experimental data which substantiate the resonance are presented. Techniques by which a stable, well-matched discharge may be maintained by means of a UHF source are described. By using a mercury discharge, the experimental configuration is greatly simplified.

"As a side effect of the harmonic generation investigation, parametric oscillations at half the driving frequency are reported. These oscillations are shown to be the result of spatial variations and substantiate that the nonlinear mechanisms are reactive in nature. The density at which the oscillations occur also substantiates the resonance behavior of the plasma. While parametric effects have previously been observed in plasmas, oscillations of the strength obtained have not been reported."

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